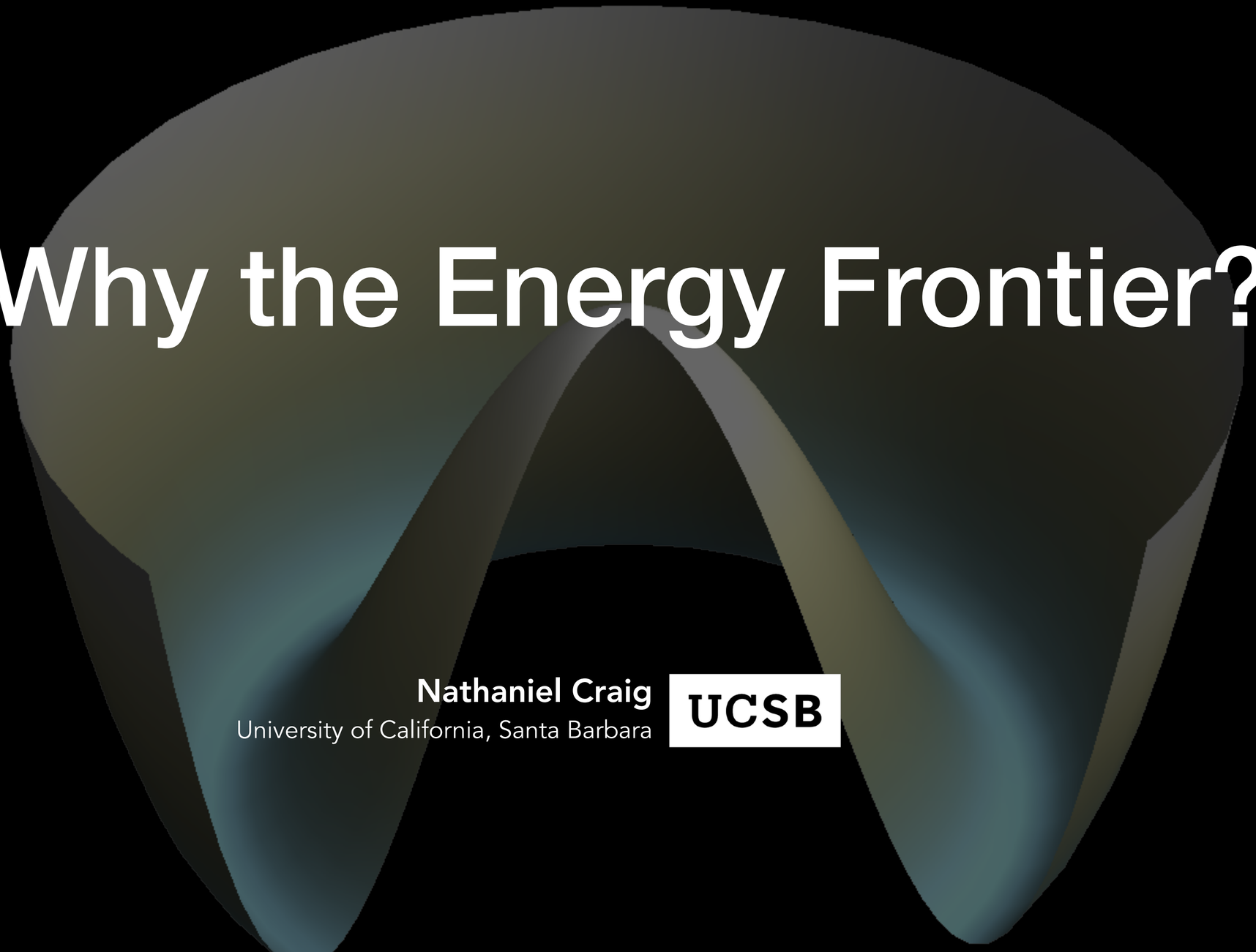
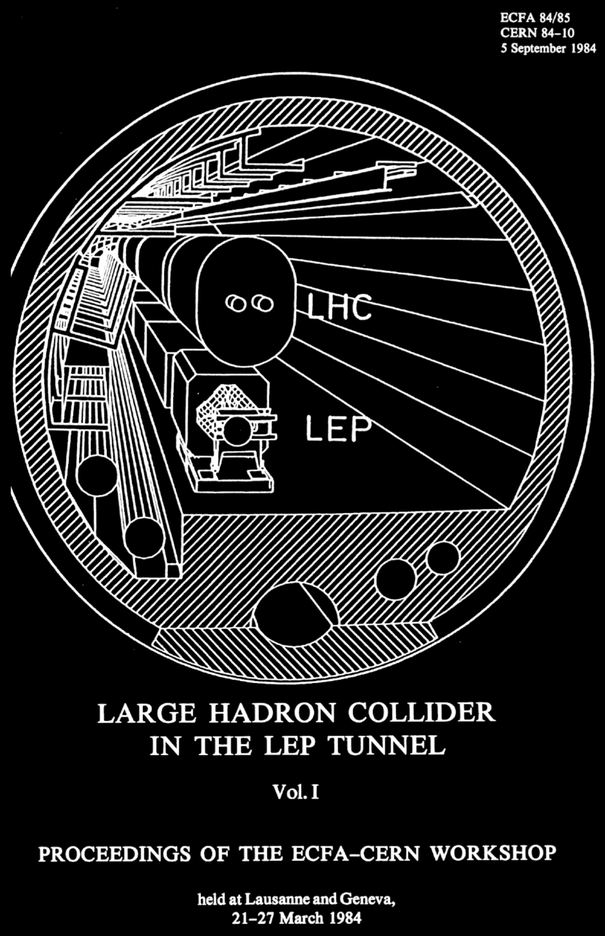


Why the Energy Frontier?

Nathaniel Craig
University of California, Santa Barbara
UCSB

Fermilab Muon Collider Physics & Detector Workshop **12.15.22**

Vision circa 1984



Satisfied with these successes, we have now to face deeper questions such as:

what is the origin of mass?
what kind of unification may exist beyond the standard model?
what is the origin of flavour?
is there a deeper reason for gauge symmetry?

We have simply too many a priori plausible hypotheses concerning the nature of symmetry breaking in the standard model. Experimentation in the TeV range at the constituent level is bound to provide most essential clues, and the present successes of the $p\bar{p}$ collider are a very strong encouragement to go to higher energies and to higher luminosities in hadron-hadron collisions.

Vision circa 2022

Vision circa 2022

✓ What is the origin of mass?
What kind of unification may exist?
What is the origin of flavor?
Is there a deeper reason for gauge symmetry?

Vision circa 2022

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+ What is the nature of the neutrino sector?

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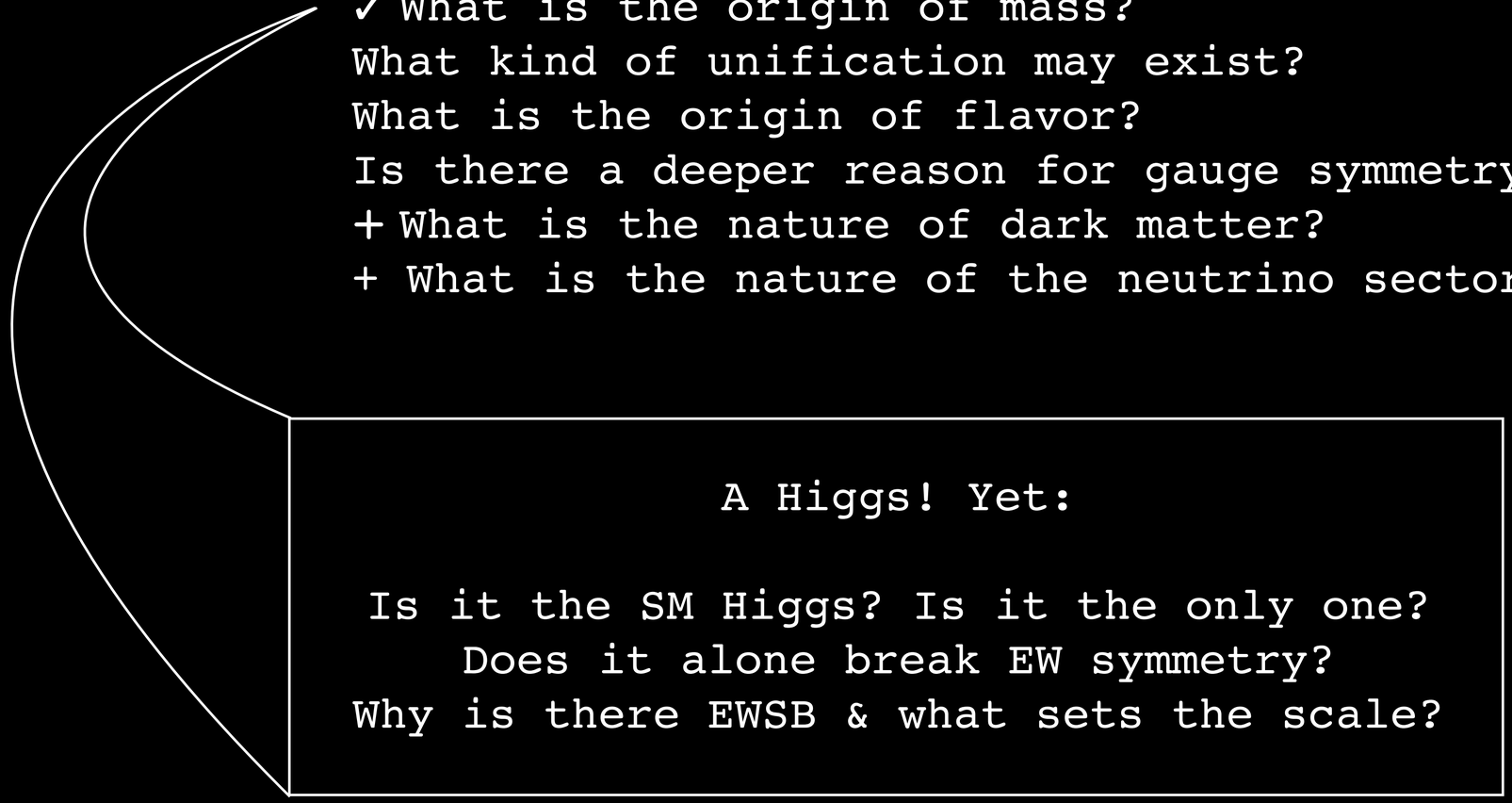
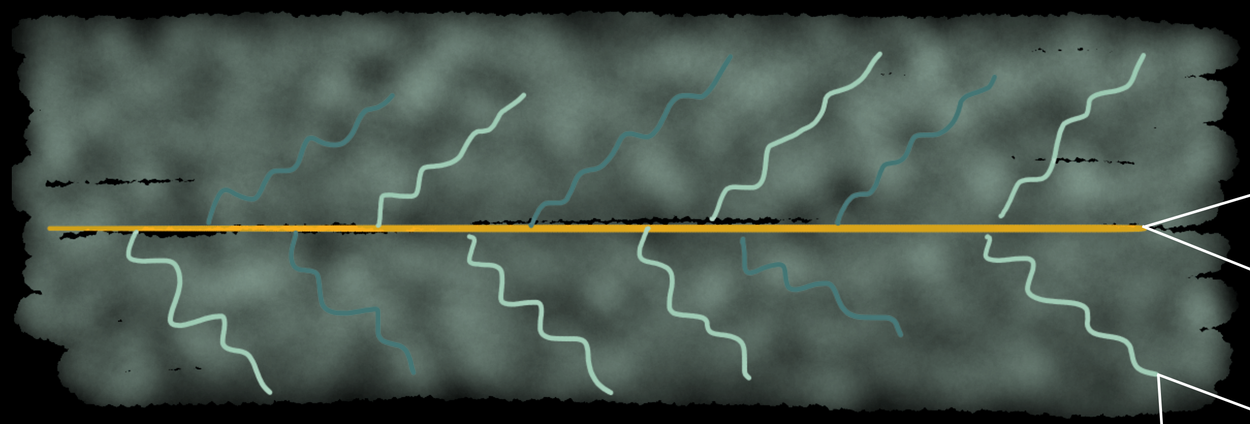
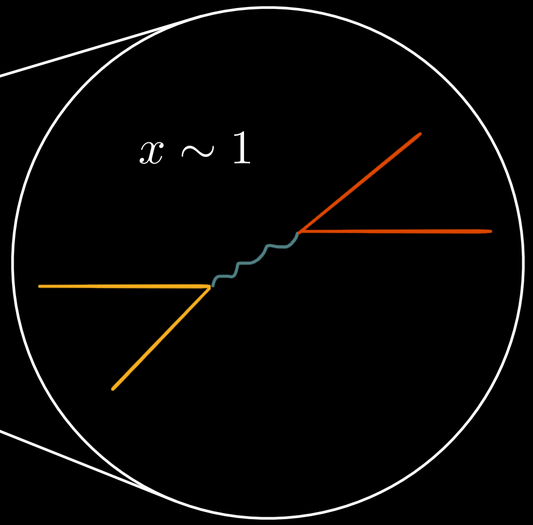
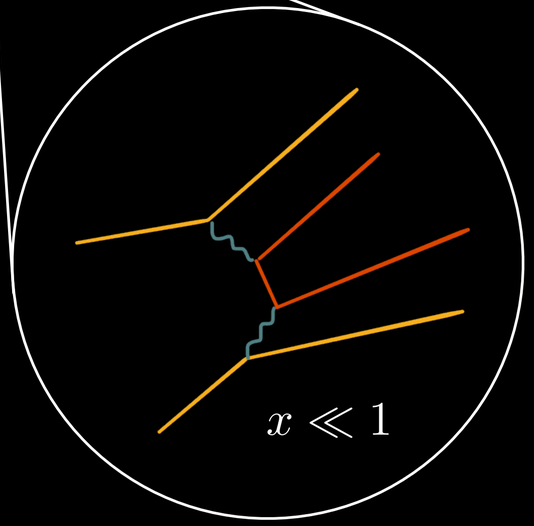


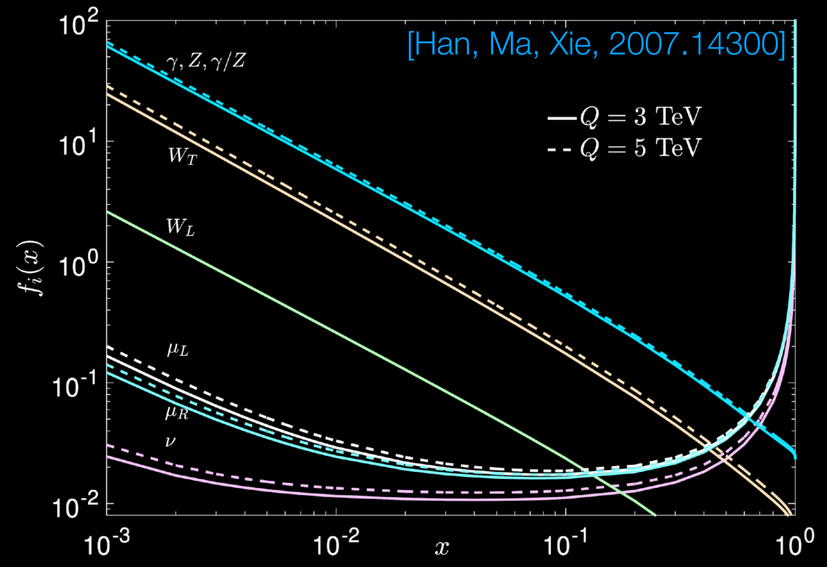
If these are the questions, why are muons the answer?

The Quantum Muon







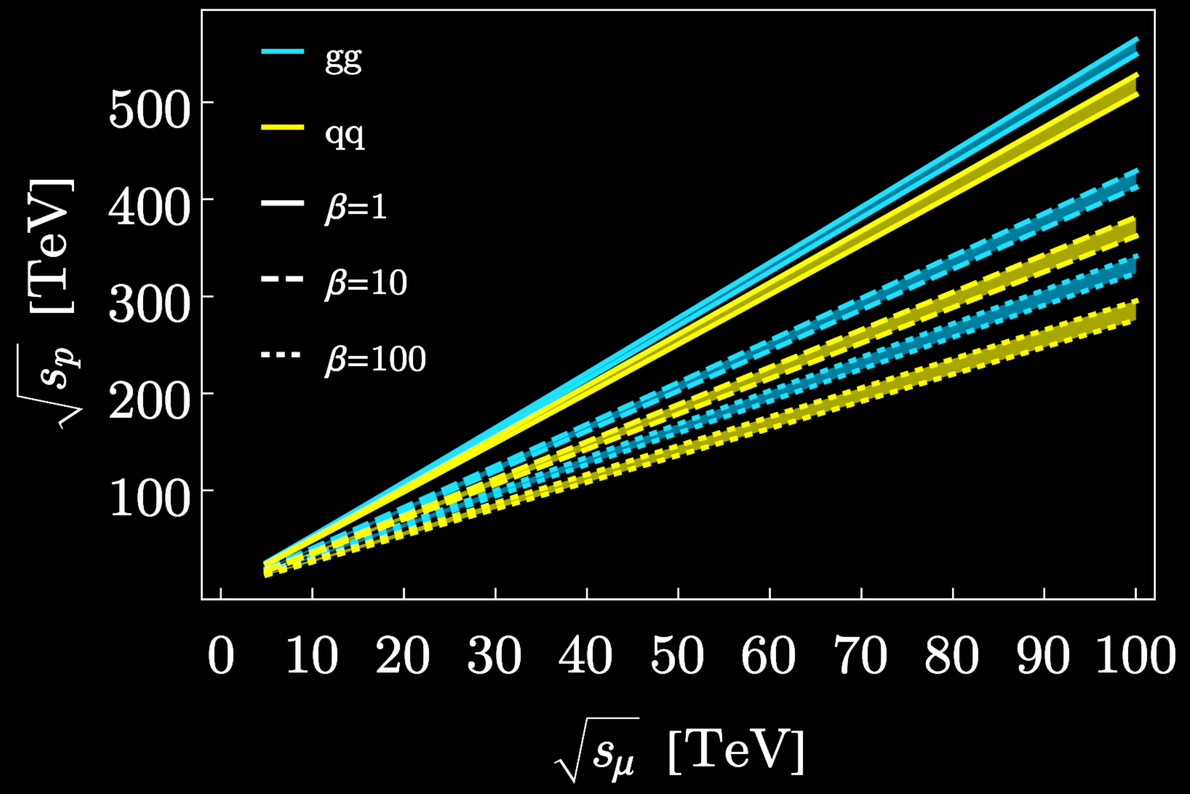


Muon annihilation
deploys the entire energy of the collider

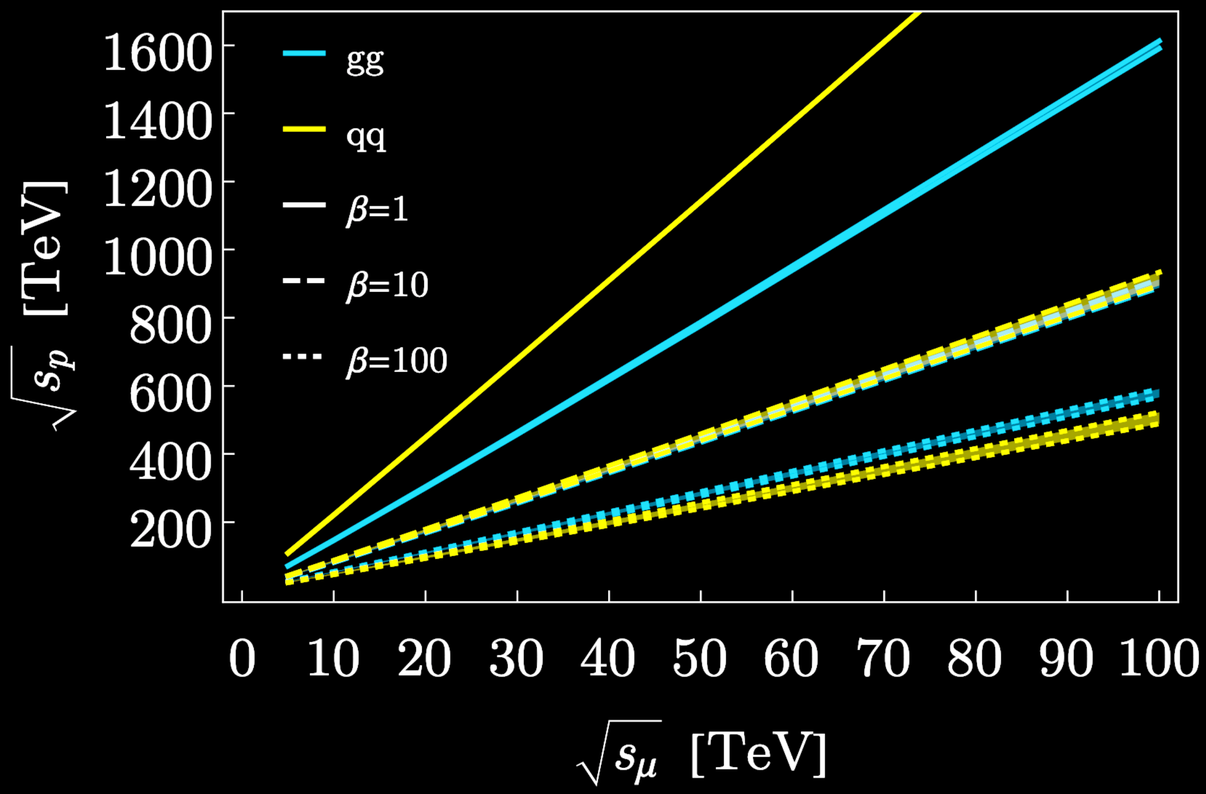
Vector boson fusion
leverages the muon's virtual boson content

Muon annihilation & pp equivalents

2-to-1 production



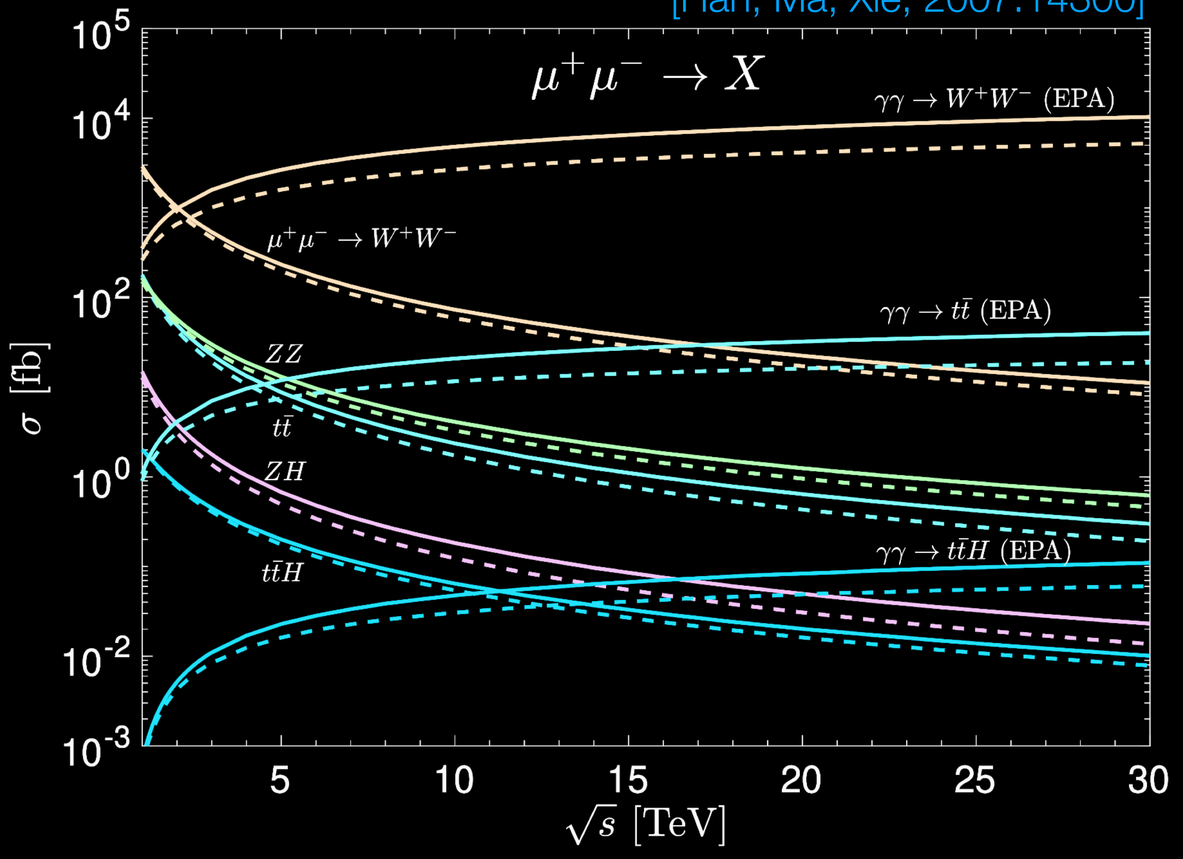
2-to-2 production



(Bands are NNPDF3.0 LO vs. CT18NNLO)

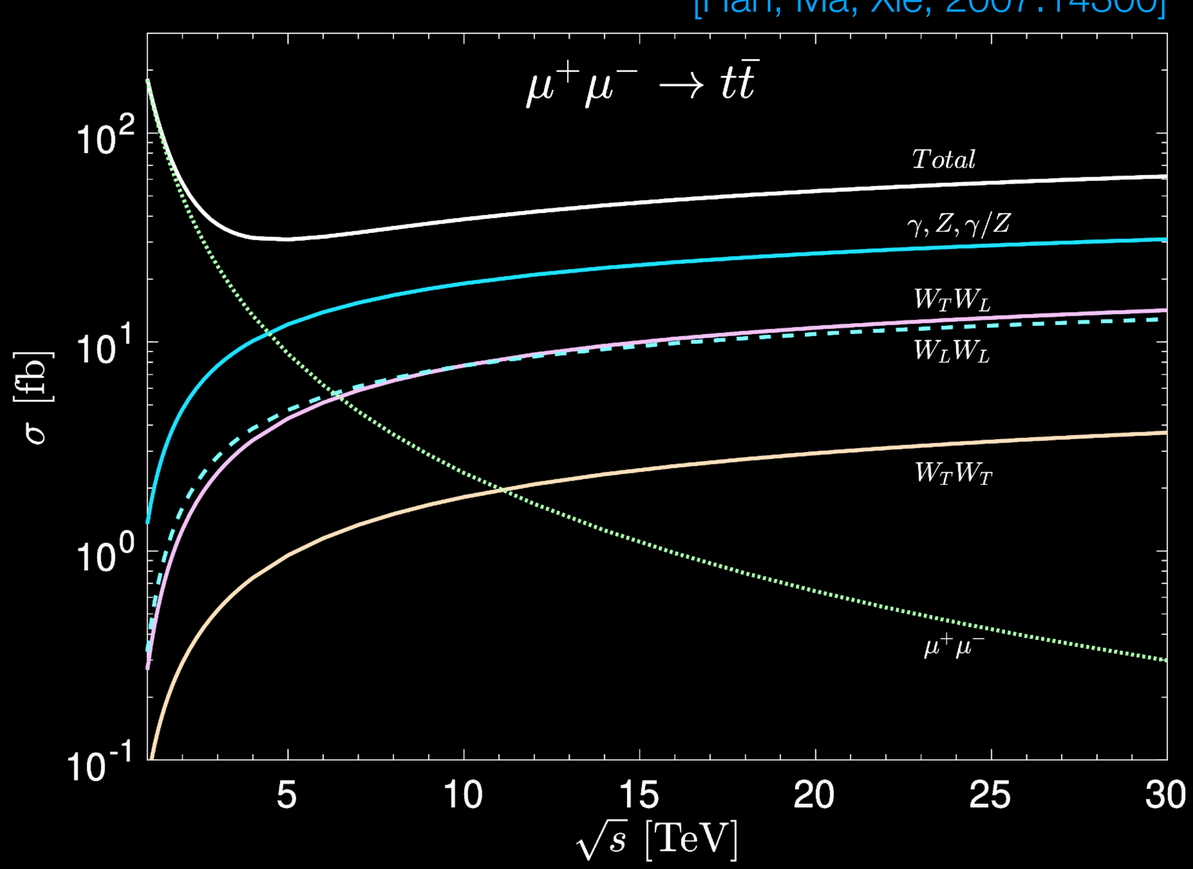
VBF: μCs as Vector Factories

[Han, Ma, Xie, 2007.14300]



VBF dominates well above threshold due to logarithmic growth with E_{CM}

[Han, Ma, Xie, 2007.14300]



Longitudinal polarizations play a key role, making an extraordinary laboratory for EWSB

c.f. [Costantini et al. 2005.10289]

How do muons illuminate the physics vision?

What is the origin of mass?

A Higgs! Yet…

What is the origin of mass?

A Higgs! Yet…

"The more ambitious goal…is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald."

–Frank Close

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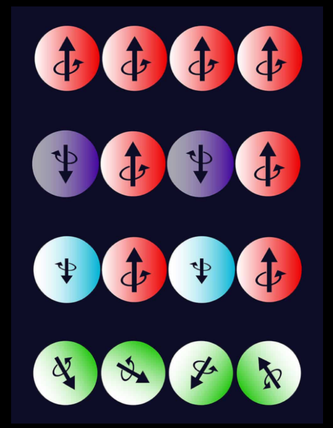
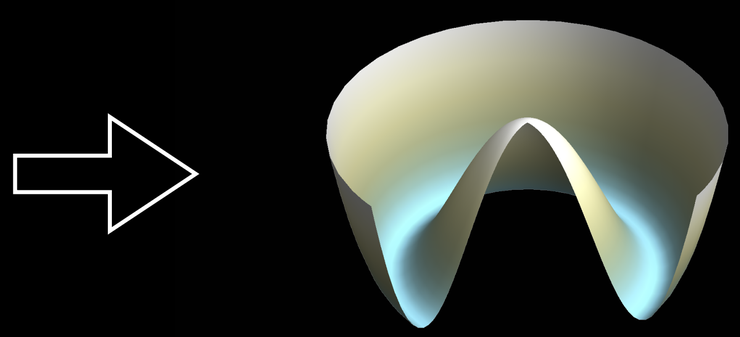
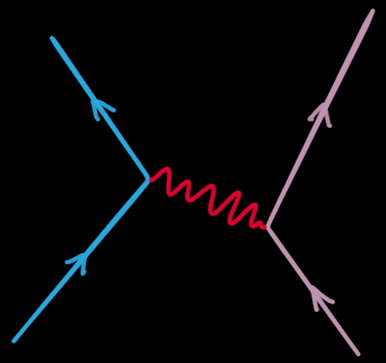
A superconducting analogy:



High-Tc Superconductors



Ginzburg-Landau Theory



Low-Tc Superconductors (BCS)

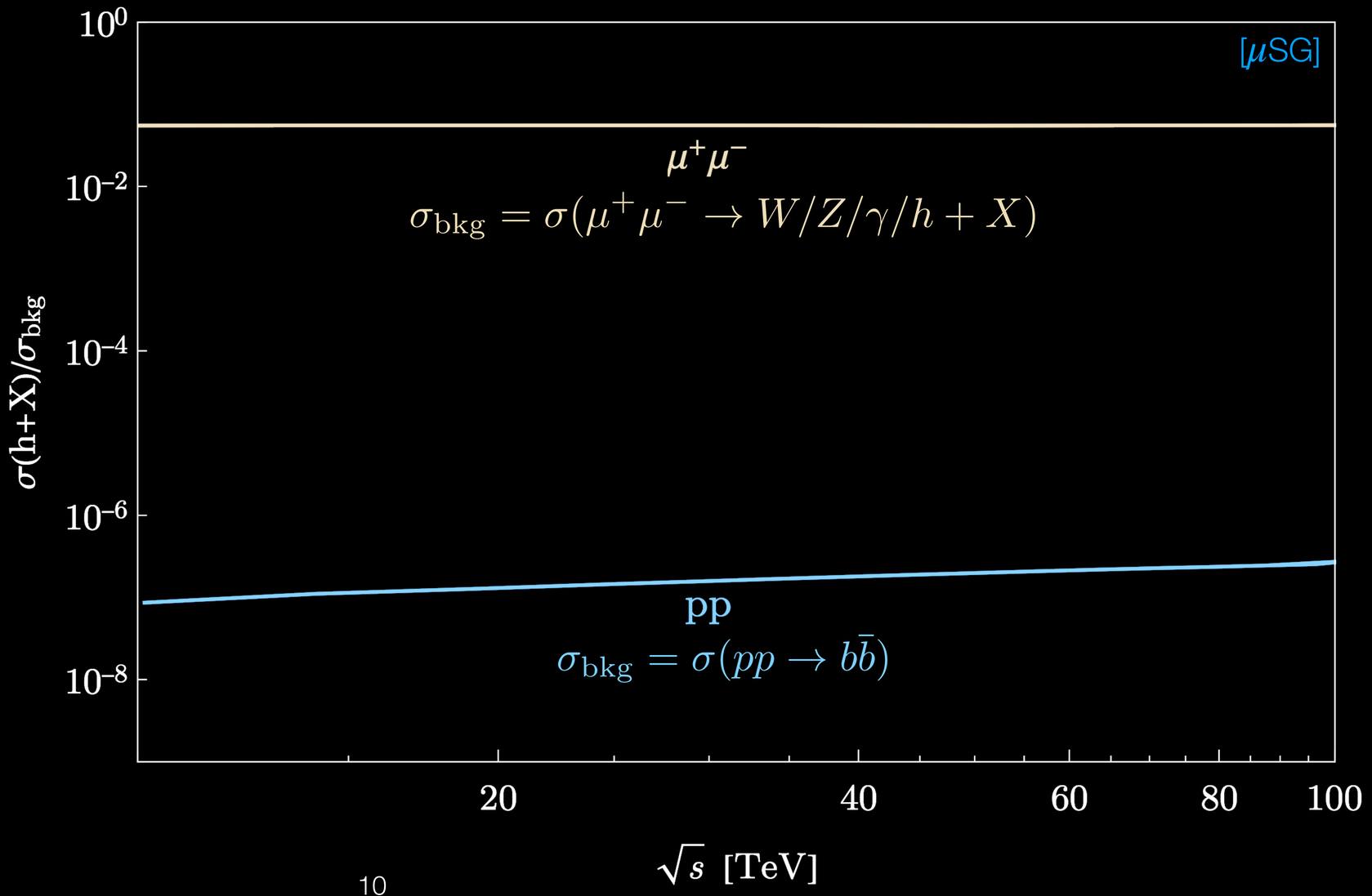
What is the origin of mass?

A Higgs! Yet:
Is it the SM Higgs?
Is it the only one?
EWSB by it alone?
Why is there EWSB?
What sets the scale?

The Higgs itself is key.

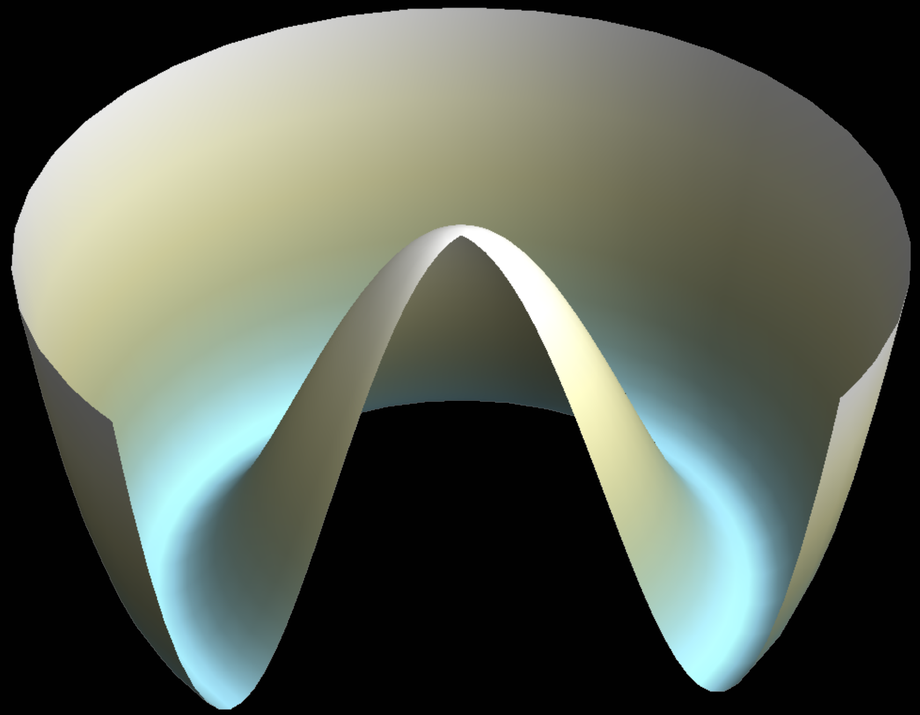
Any deviation in its properties from SM predictions is a telltale sign of new physics.

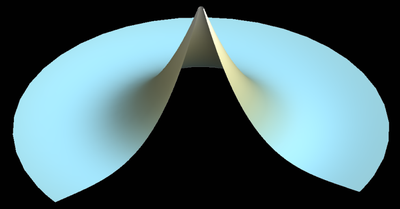
S/B favorable at a μC.

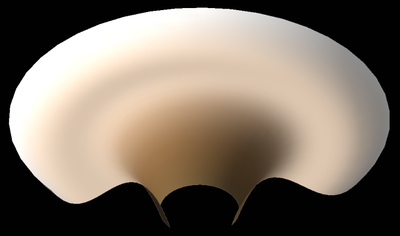


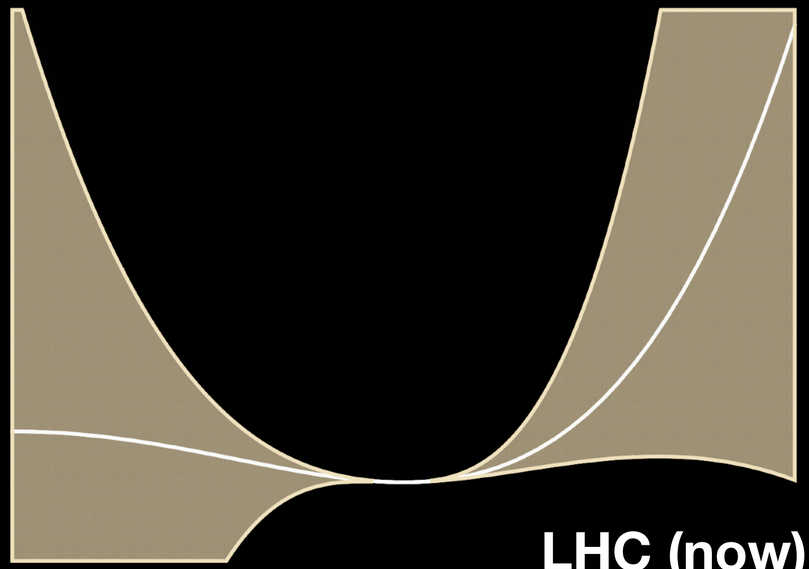
Is it the SM Higgs?

See talks by I. Low & M. Forslund





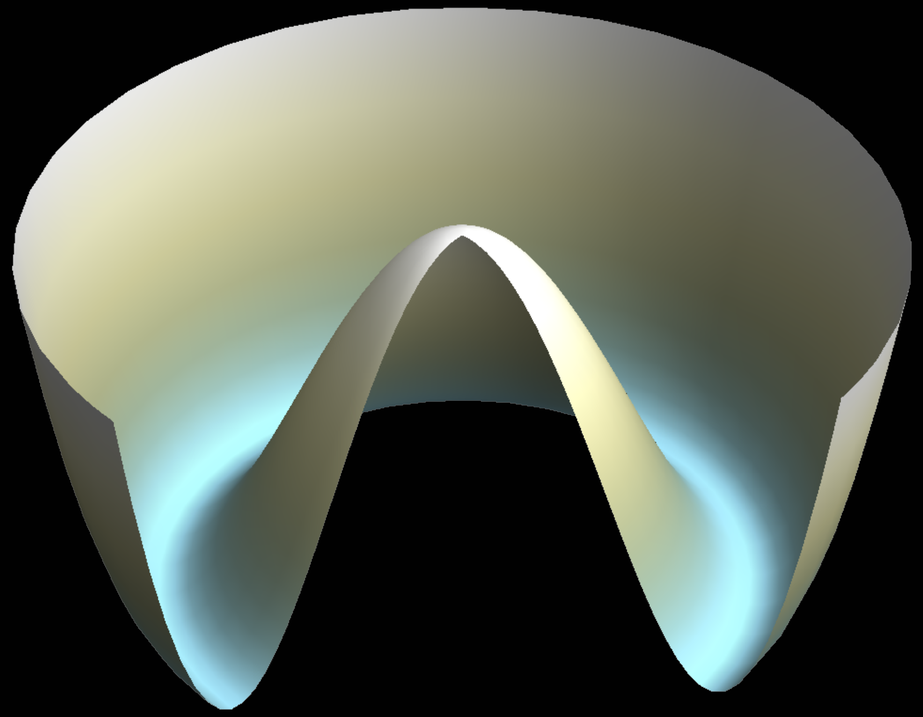


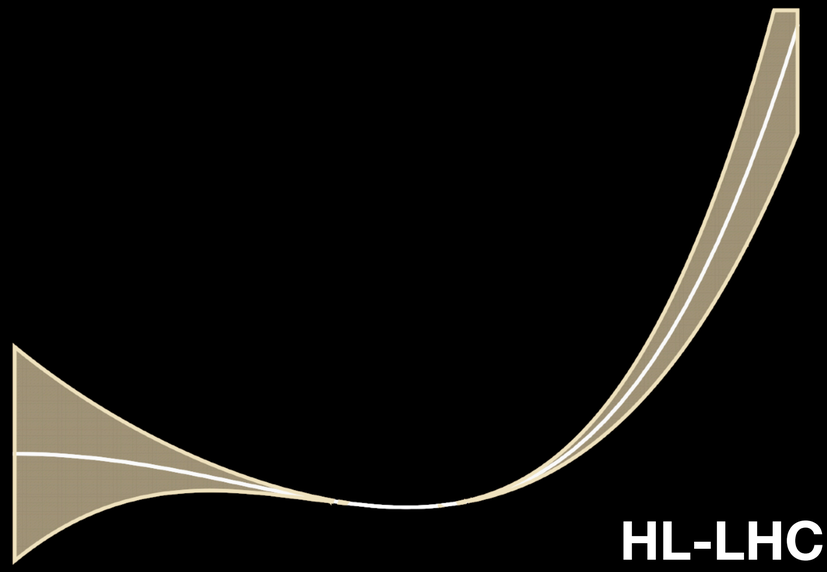


LHC (now)

(If you like this way of presenting Higgs self-coupling precision, please feel free to use it! The inspiration came from conversations with R. Petrossian-Byrne.)

Is it the SM Higgs?

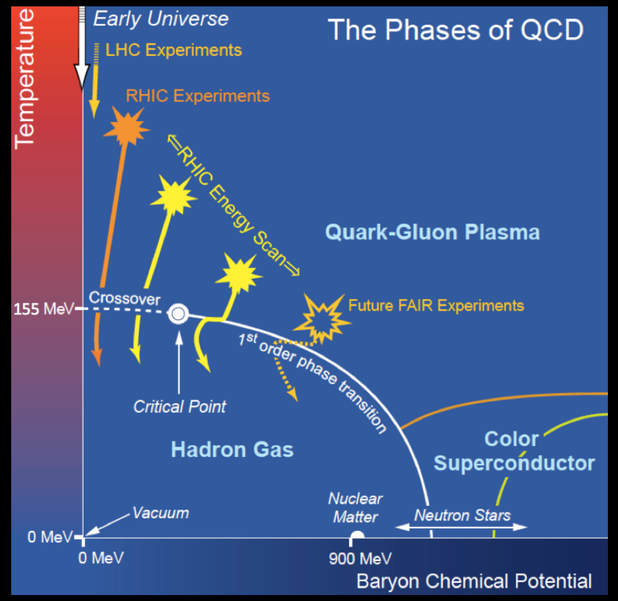




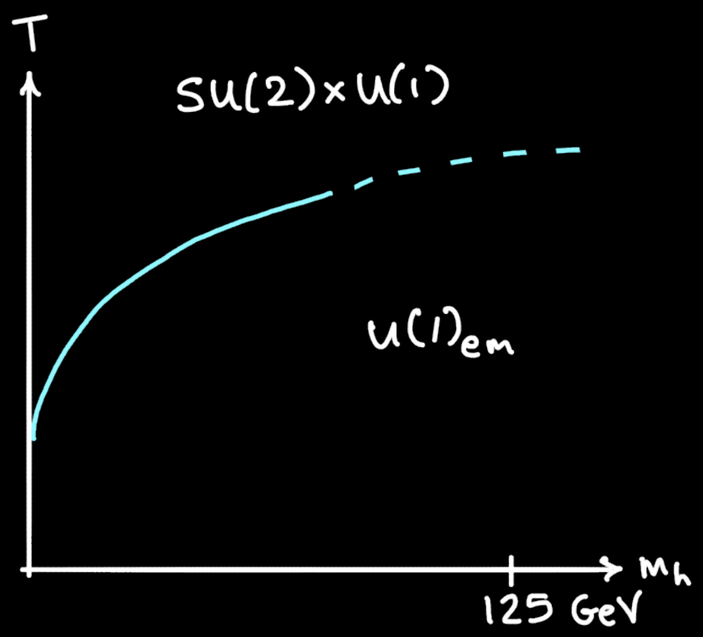
HL-LHC

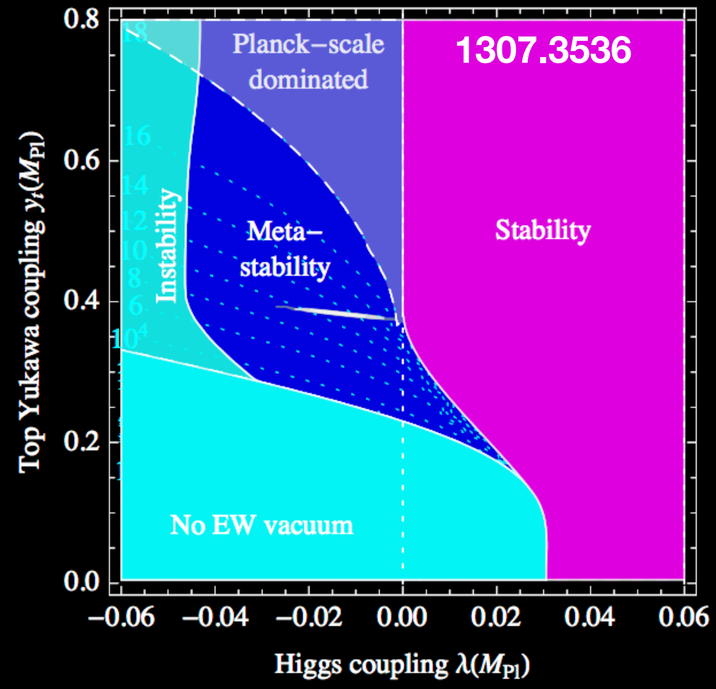
μC (10 TeV)

The birth and death of the Universe?



[2015 NSAC LRP / 1501.06477]



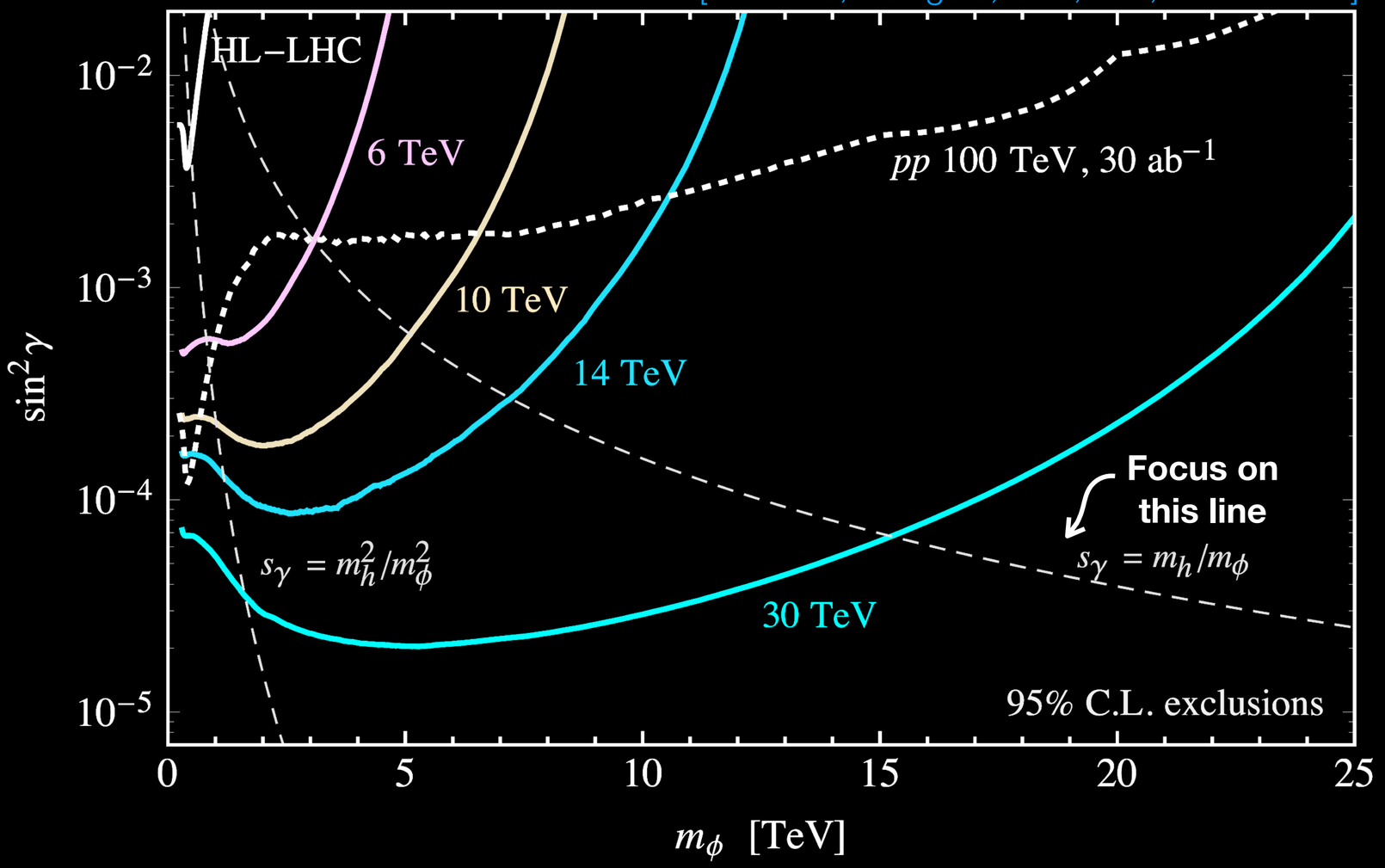


First-order electroweak phase transition?

Vacuum stability?

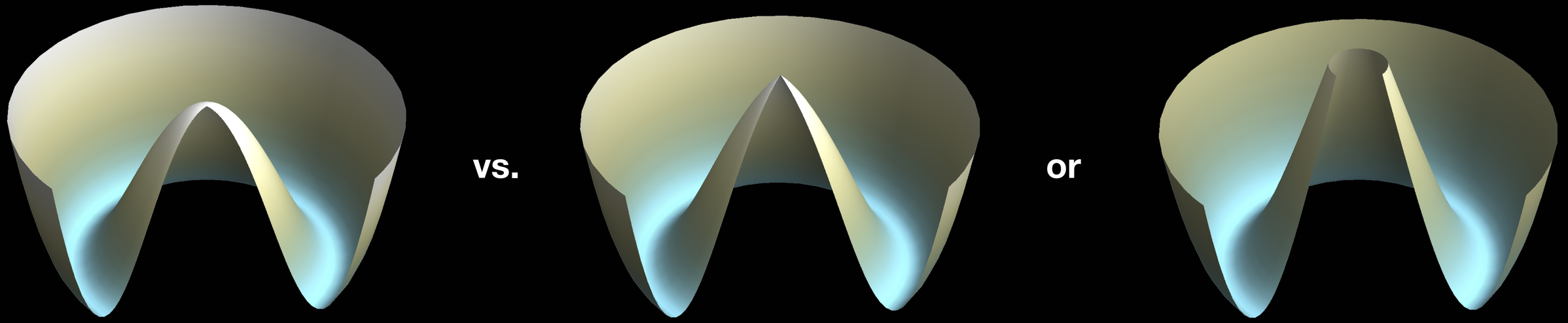
Is our Higgs the only one?

[Buttazzo, Redigolo, Sala, Tesi, 1807.04743]



Does it alone break EW symmetry?

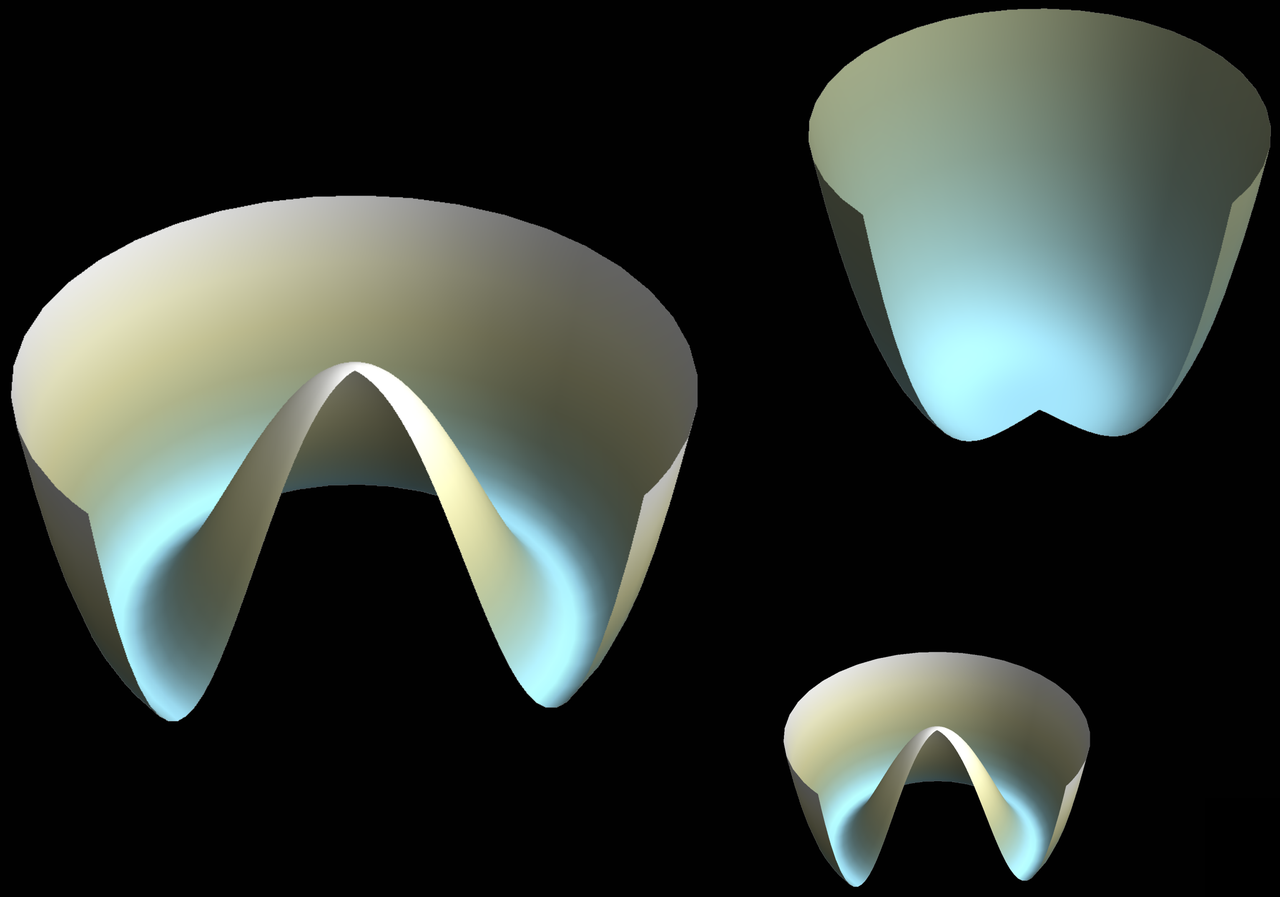
(+Is there a ~~deeper reason for~~ gauge symmetry?)



Best probed in vector boson scattering with 3+ bosons in the final state…
[Chang & Luty ’19, Falkowski & Rattazzi ’19, Cohen, NC, Lu, Sutherland ’21]

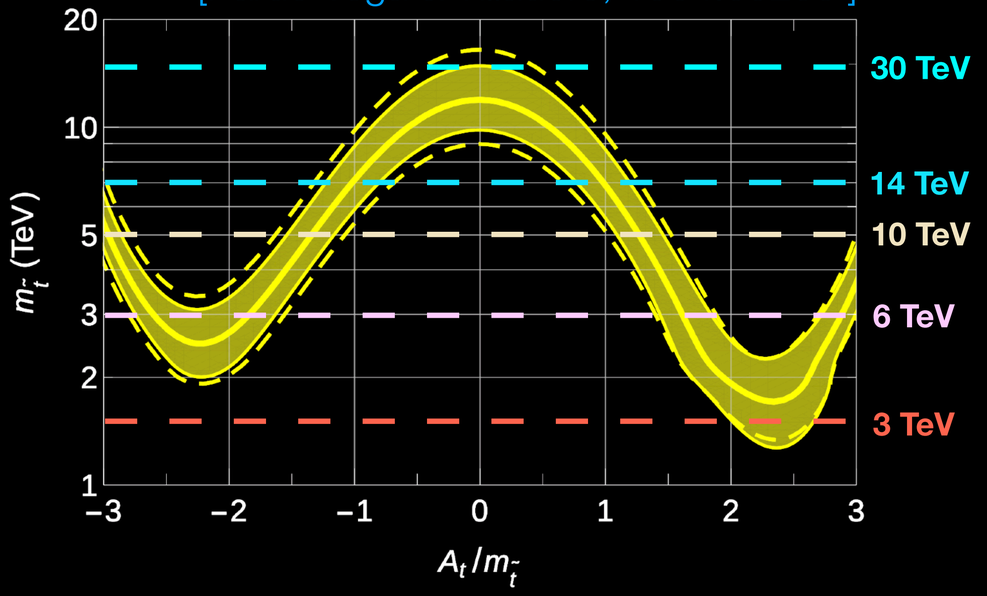
Why EWSB? What sets the scale?

Theories that predict the Higgs mass & EWSB provide sharp targets for new physics.



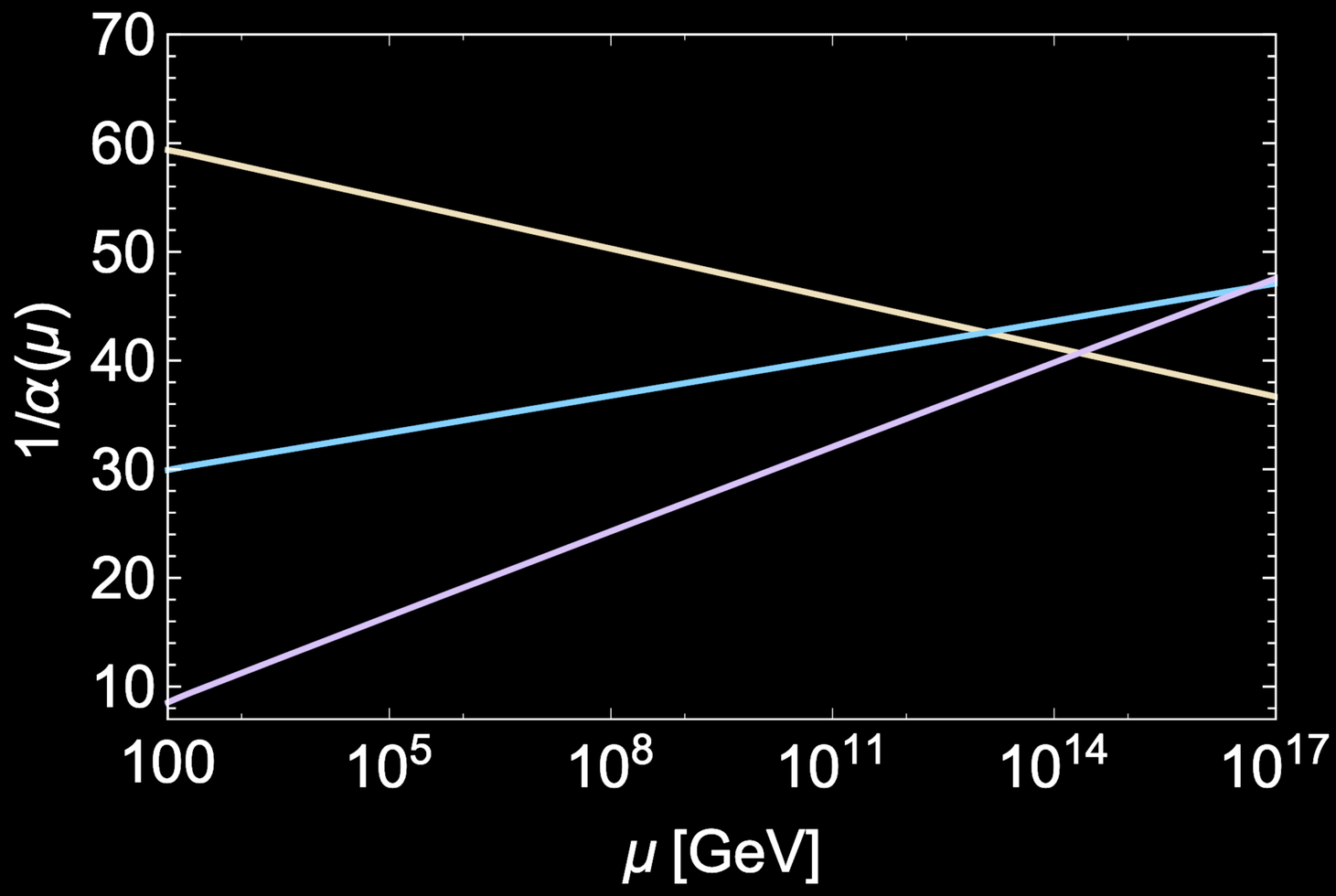
Direct targets set by the observed Higgs mass (e.g. supersymmetry)

[Pardo Vega & Villadoro, 1504.05200]



Unification beyond the Standard Model?

Running of couplings in the Standard Model tantalizingly hints at unification, but the intersection is imperfect & scale too low.



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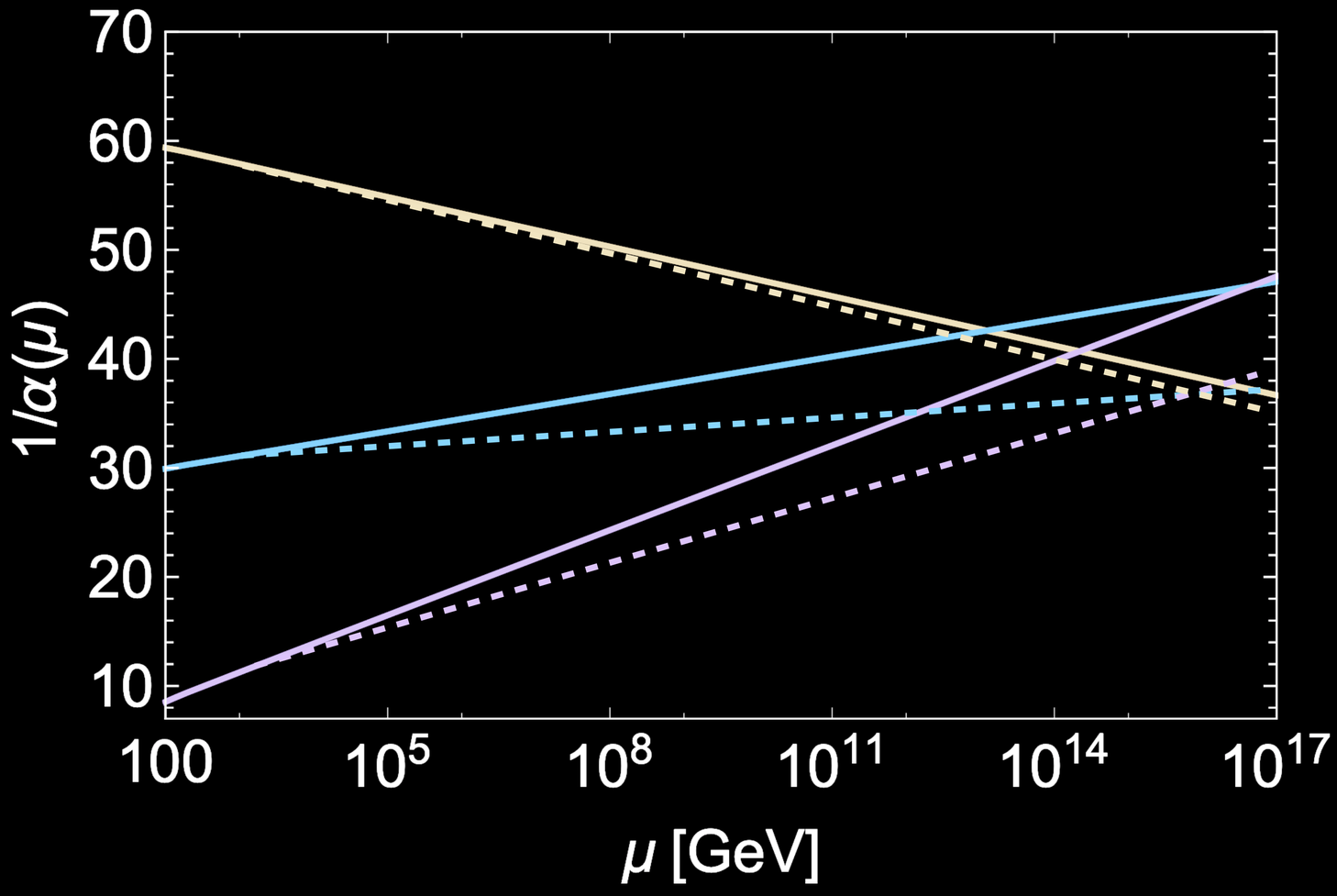


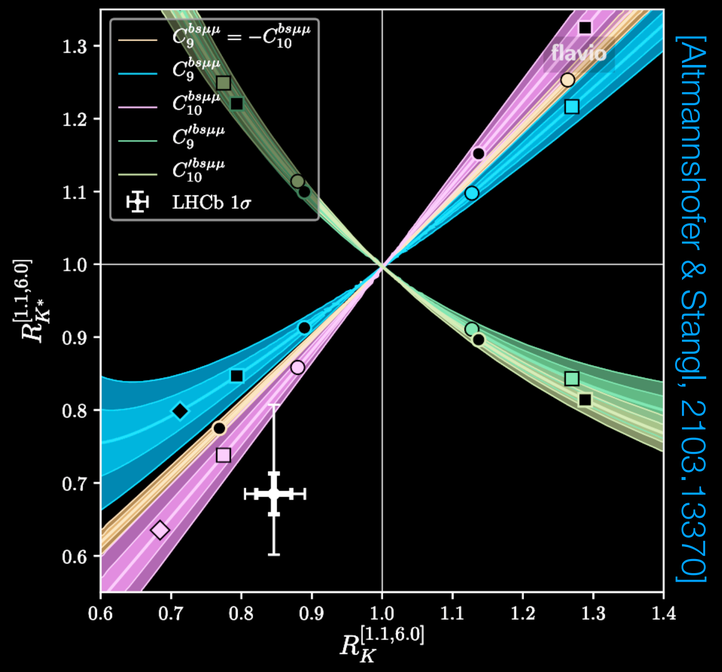
New particles at TeV energies sharpen the prediction & raise the scale: clear targets for a high-energy muon collider, reach to ~$E_{CM}/2$

What is the origin of flavor?

First high-energy accelerator to primarily collide second-generation fermions.

Direct access to hypothetical new particles associated with flavor structure

Indirect access to flavor structure via lepton flavor violating operators



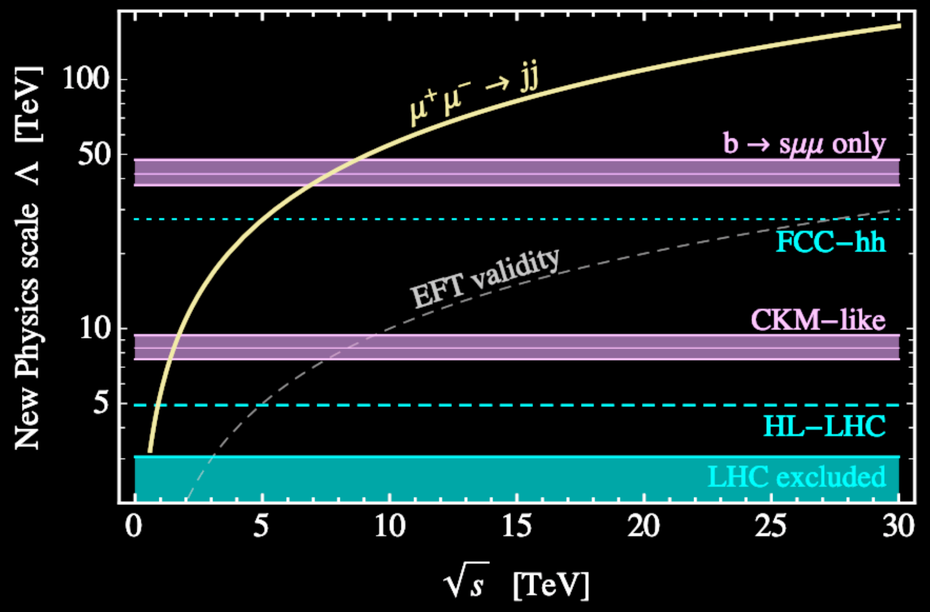
[Altmannshofer & Stangl, 2103.13370]

An outstanding probe of explanations for **lepton flavor universality violation**

[Huang, Queiroz, Rodejohann, 2101.04956; Huang, Sana, Queiroz, Rodejohann, 2103.01617, Asadi, Capdevilla, Cesarotti, Homiller 2104.05720]

See talk by R. Capdevilla

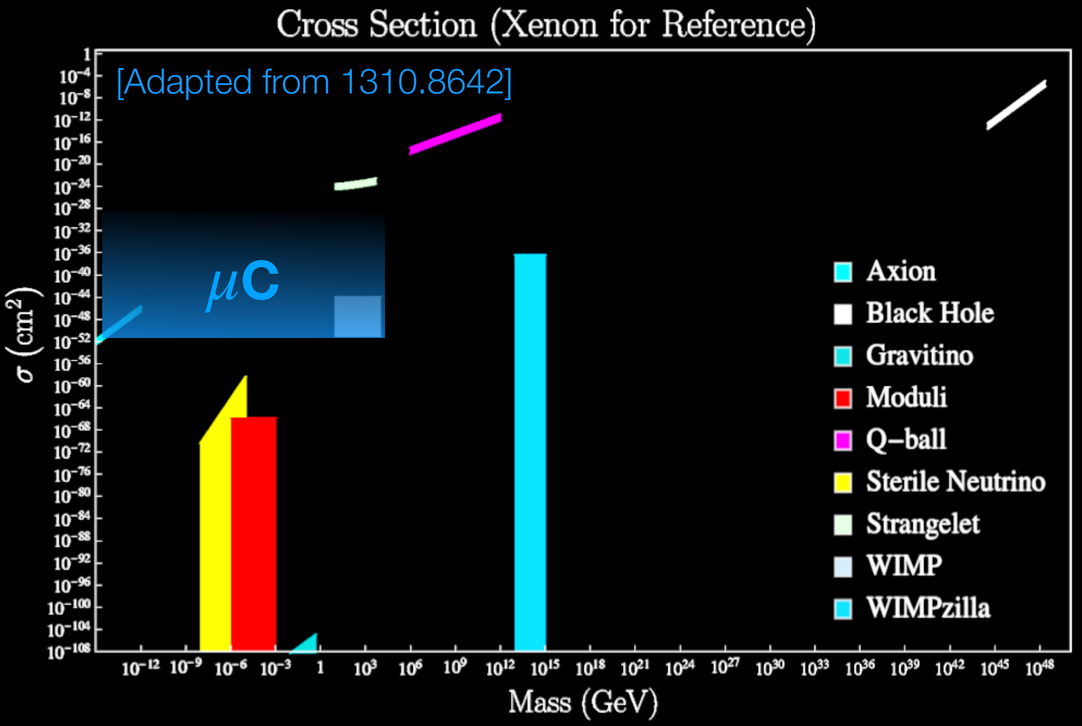
[IMCC Muon Collider Physics Summary]



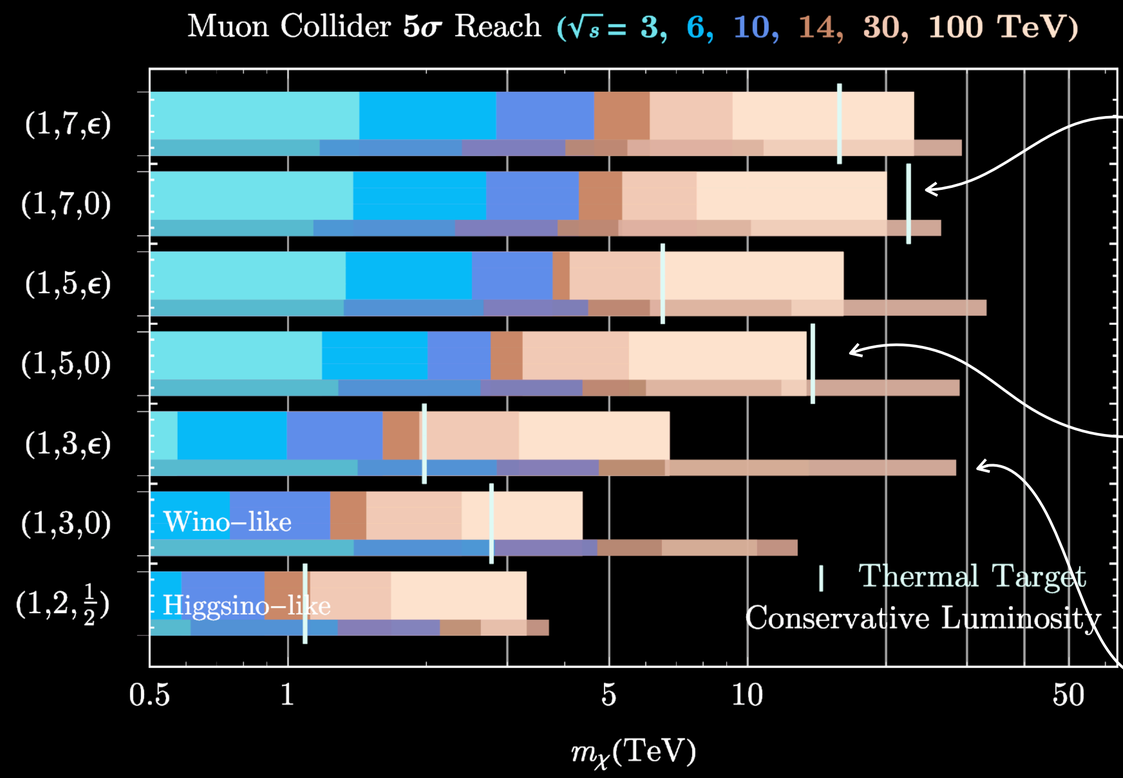
What is the nature of dark matter?

An ideal laboratory for producing & detecting weakly-interacting dark matter.

We know DM is there; coincidence of Ω_b, Ω_{dm} suggests interactions beyond gravitational



“Minimal dark matter”
(Electroweak multiplet w/ neutral lightest particle)



Target set by DM abundance (WIMP miracle)

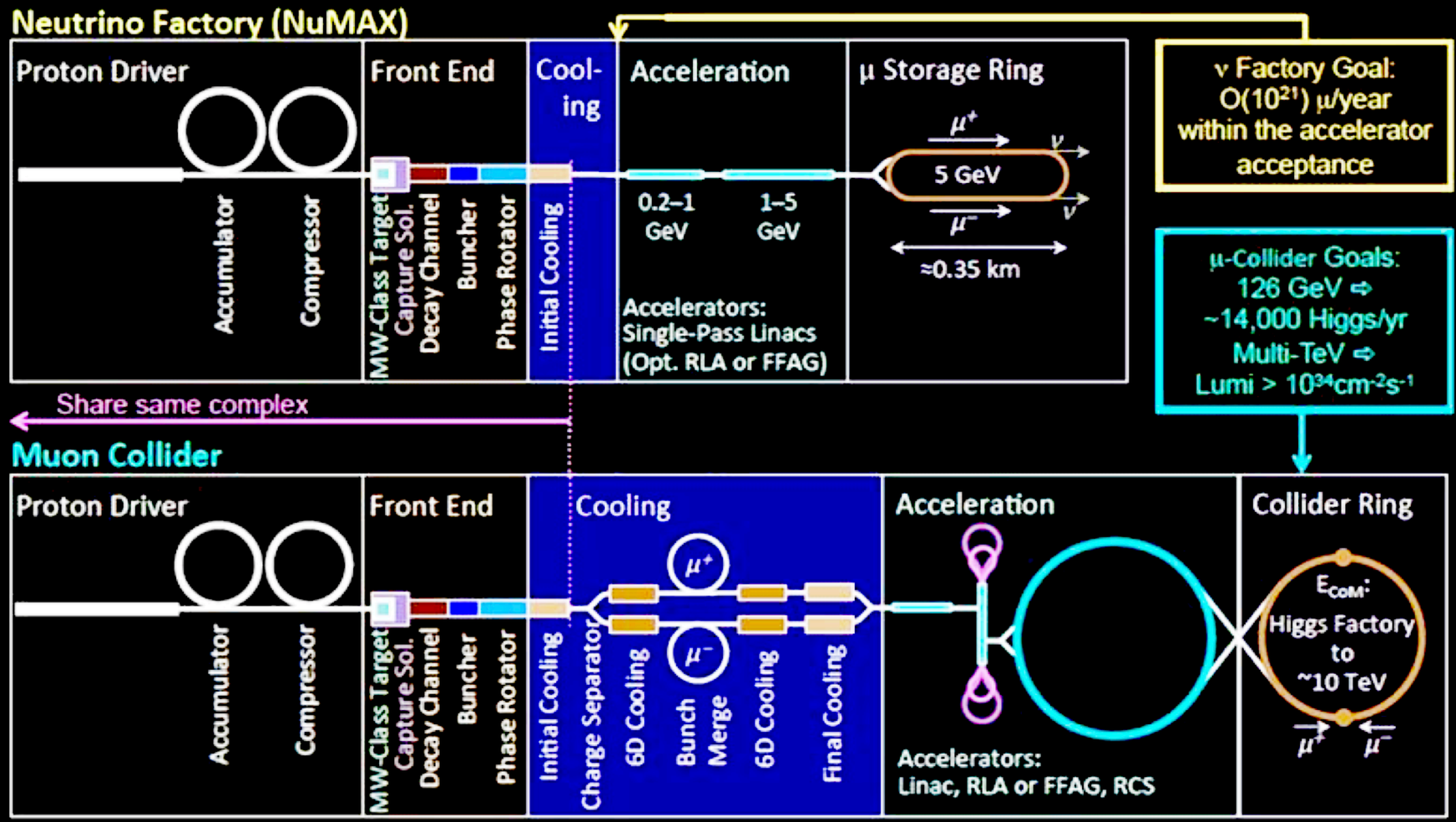
Photon + missing momentum search

Disappearing track search

[Han, Liu, Wang, Wang, 2009.11287, lumi updated for μSG]
see also [Capdevilla, Meloni, Simoniello, Zurita 2102.11292]

See talk by L-T Wang

What is the nature of the neutrino sector?



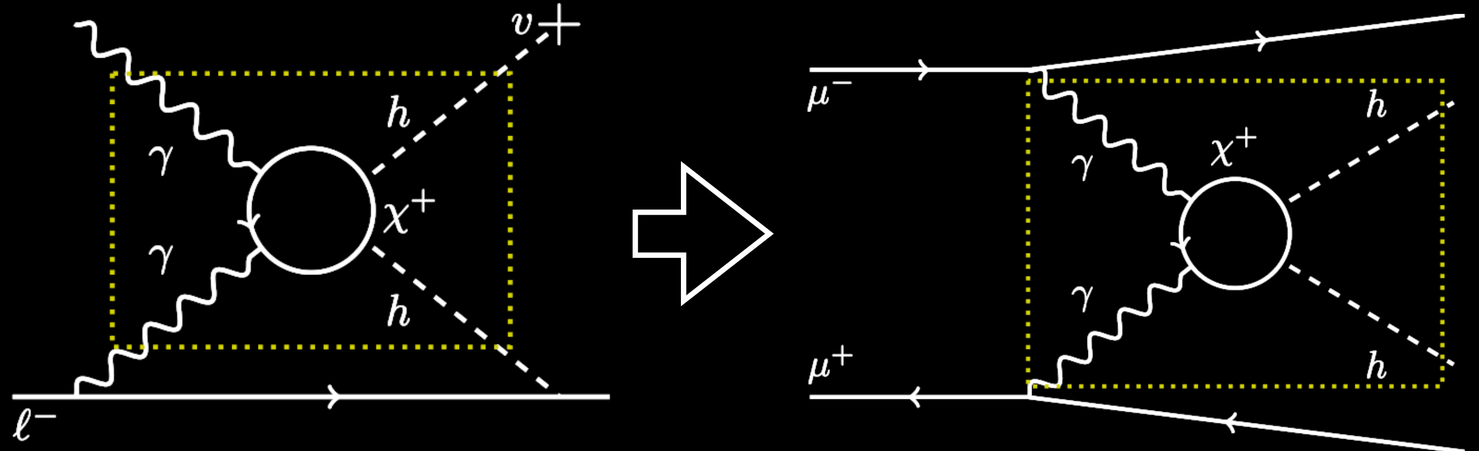
[Delahaye et al. 1803.07431]

- Muon storage ring-based neutrino factory synergistic w/ development of high-energy muon beams.
- Physics opportunities in neutrino radiation, mu-nu collisions, or nu-nu collisions at high-energy muon collider itself?

See talks by K. Yonehara & K. Lyu

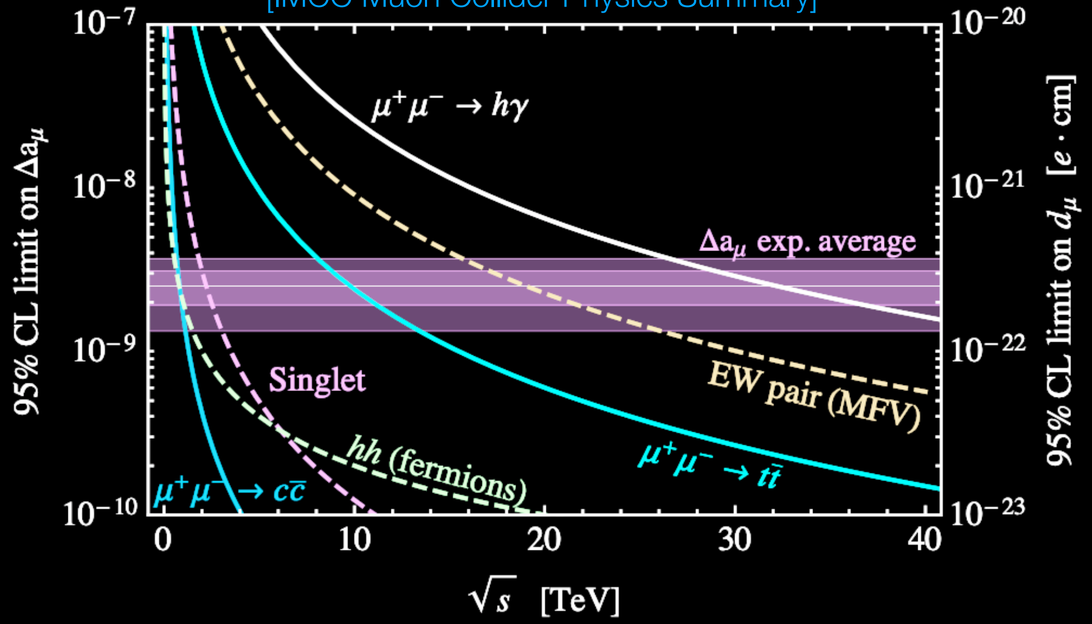
Compelling complementarity

E.g. next-gen. **electron EDM** experiments sensitive to ~20 TeV particles in Barr-Zee diagrams; same diagram probed in muon colliders



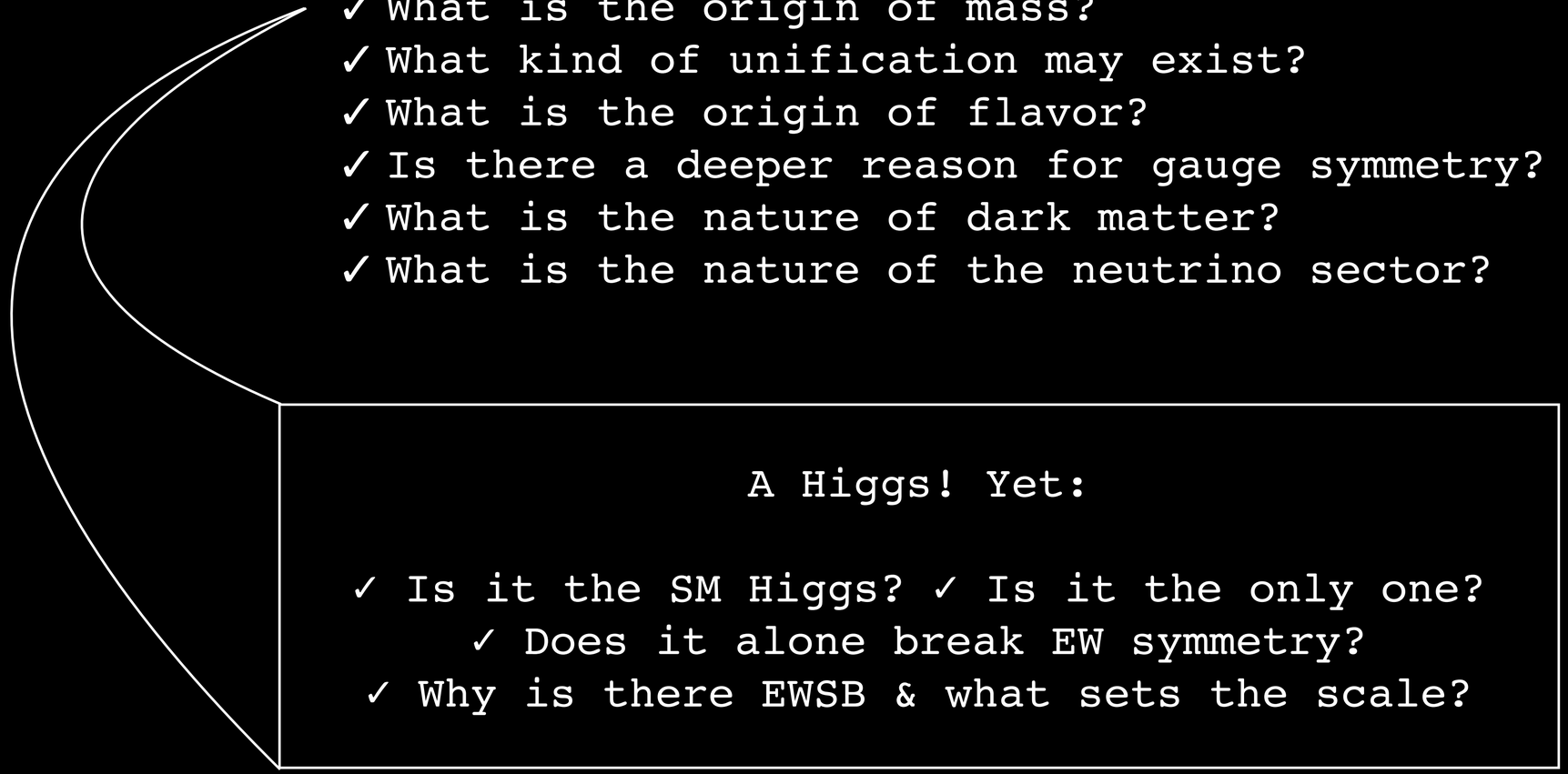
Any new physics contributions to **Muon g-2** efficiently probed at muon colliders [Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277; Buttazzo & Paradisi, 2012.02769; Capdevilla, Curtin, Kahn, Krnjaic, 2101.10334; Chen, Wang, Yao 2102.05619; Yin, Yamaguchi 2012.03928]

[IMCC Muon Collider Physics Summary]



See talks by G. Krnjaic, R. Bernstein, C. Cesarotti, D. Acosta

Vision circa 2022



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A Higgs! Yet:

✓ Is it the SM Higgs? ✓ Is it the only one?
✓ Does it alone break EW symmetry?
✓ Why is there EWSB & what sets the scale?

The muons are calling, and we must go.

Thank you!